The Dual-Spin Satellite Attitude Stabilization Concept

Engineering Case Study ECL 1006, the story of the surprising instability in the orientation of the first U. S. satellite (Explorer 1), describes the following solution to the problem of satellite spin-stabilization: "As a result of this new understanding all spin-stabilized satellites after Explorer [I] were designed to spin about the axis of maximum moment of inertia[1]."

The indicated resolution of the stability problem of Explorer I was based on oversimplified arguments, and the widely accepted conclusion quoted above is unnecessarily restrictive. In fact, a force-free spacecraft can also spin stably about its axis of *minimum* inertia, as long as a sufficiently effective passive damper is housed in a despun or counter-rotated part of the spinning vehicle. (In practice, an actively controlled torque-motor is incorporated to compensate for bearing friction, and the despun part of the vehicle often serves other functions than housing the damper, but in principle the stability of the spin axis can be obtained with frictionless bearings and a completely passive damper.)

A vehicle consisting of two primary components free to perform relative rotations about a common bearing axis is called a "dual-spin" vehicle, and the idea of stabilizing such a vehicle by spinning one part (the "rotor") while the other part (the "despun platform") rotates more slowly or not at all is called the *dual-spin attitude stabilization concept.* This case study describes the evolution of this concept from early rejection to current pre-eminence among methods of attitude control of space vehicles.

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[1] Numerical superscripts designate references listed at the end of this study.

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Outline

I. Introduction

Even the most primitive artificial earth satellite must maintain communications with the ground if it is to have any value to man, and ground communication is greatly facilitated when the attitude, or orientation, of the vehicle can be controlled. Therefore problems of attitude dynamics or rotational dynamics found a new importance with the dawning of the space age. This case deals with the development of a particular method of attitude control called the *dual-spin attitude stabilization concept,* which has in the late 1960's very rapidly become one of the dominant attitude control methods in this dynamic industry.

The evolution of the dual-spin satellite idea was not marked by a textbook pattern of orderly, rational progress from basic principles to technological execution. Instead it seems, from today's perspective, to be characterized by a combination of human errors and oversights, personal triumphs and frustrations, blind fortune and misfortune, and finally by that critical combination of engineering analysis and managerial promotion that spells success in the aerospace industry.

The *dual-spin attitude stabilization concept* can be described in the complex mathematical language of the research journals, as numerous papers attest (see References). Our purpose here is to move the dramatic story of the development of this idea out from behind the maze of lengthy equations and technical language, so it can be appreciated by the unintiated. You must guard however against the comfortable feeling that you can understand the substantial technical questions underlying this case by reading the verbal text and noting the conclusions. In fact the lesson of this case study is in the importance of critical evaluation of the "rules of thumb" that practicing engineers too often hold sacred. As our story unfolds, you will see that on more than one occasion progress was impeded by the human tendency to cling without intellectual justification to comfortable old ideas and over-simplified generalizations.

The only mathematical concept which requires definition here is that of stability, and even in this instance we shall be content with a loose verbal definition. We say that the *solution* to a differential equation in time is *stable* if it remains arbitrarily "close" for all time to any other solution to that equation which is sufficiently "close" at one point in time. Correspondingly, a *motion* of a mechanical system is *stable* if after a sufficiently small perturbation the perturbed motion remains for all time arbitrarily "close" to the original, unperturbed motion. The motion of interest in this case involves a force-free rigid body spinning about an axis fixed in the body and fixed in inertial space. We shall call this motion *stable* if subsequent to a sufficiently small perturbation the angular velocity vector remains for all time arbitrarily close to the original spin axis of the body.

II. The story of satellite spin-stabilization

The historical antecedent of the modern *dual-spin satellite* is the simple *spinner* first represented by Explorer I and later typified by the Syncom series (see Figs. 1 and 2). The essential difference in these two satellites is in their *shape*. Both are more or less axisymmetric vehicles spinning rapidly about the symmetry axis, but this axis for the Explorer has a lower moment of inertia than any other axis, while for the Syncom this is the axis through the mass center which has the highest moment of inertia. The reason for the change in shape from Explorer I to Syncom is an exciting story in itself, as indicated by an earlier Engineering Case Study[1].

Although there once was a time when the best minds of the world were concerned with problems of rotational dynamics, the few analytically solvable problems in this field were rather soon resolved, and without the stimulus of modern technology the subject went into virtual eclipse over a hundred years ago. Thus when the time came to design satellites in 1957, there was no well-established tradition of modern research in attitude dynamics, and designers were inclined to dust off the scholarly writing of previous centuries for their ideas.

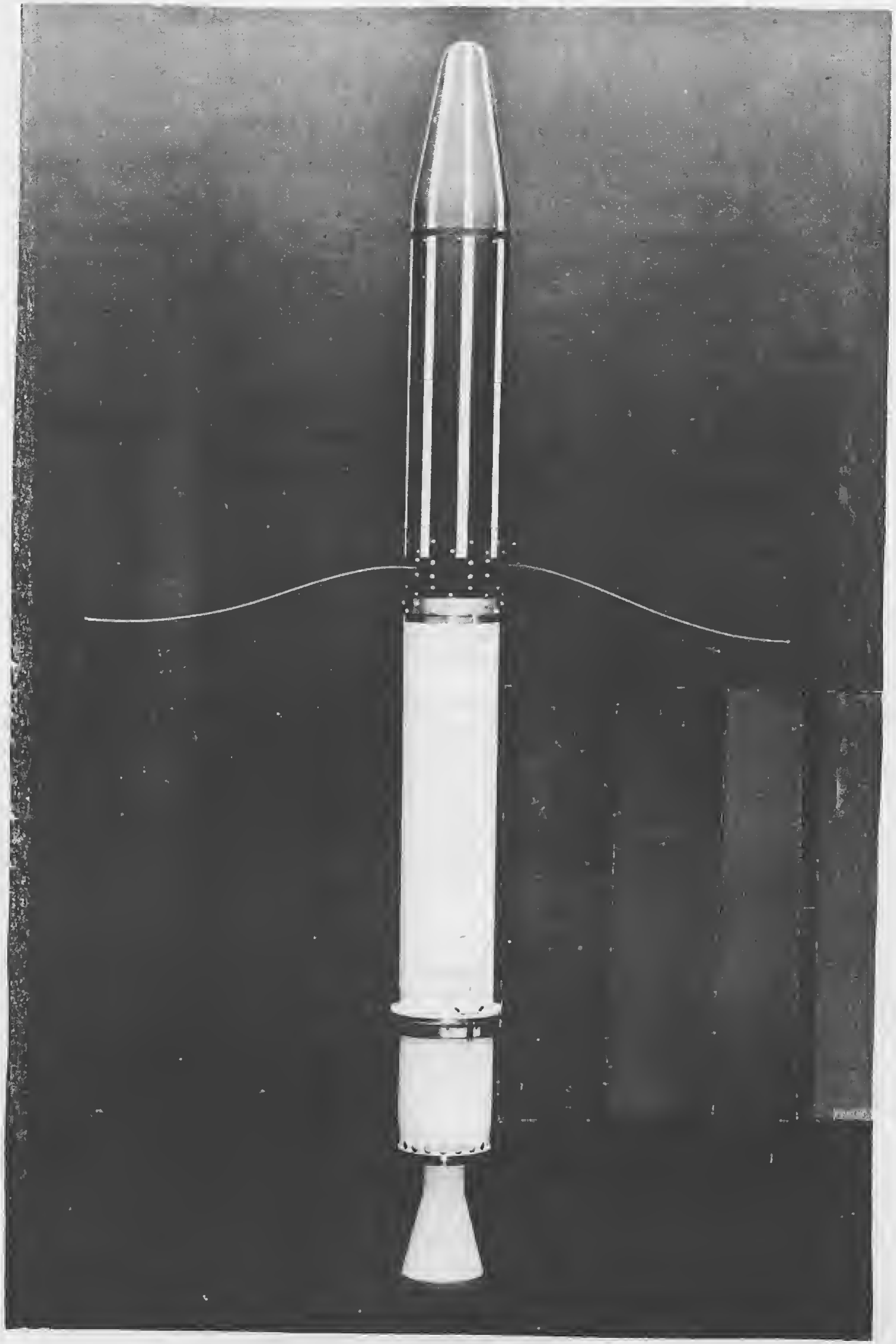

FIGURE 1. Explorer 1

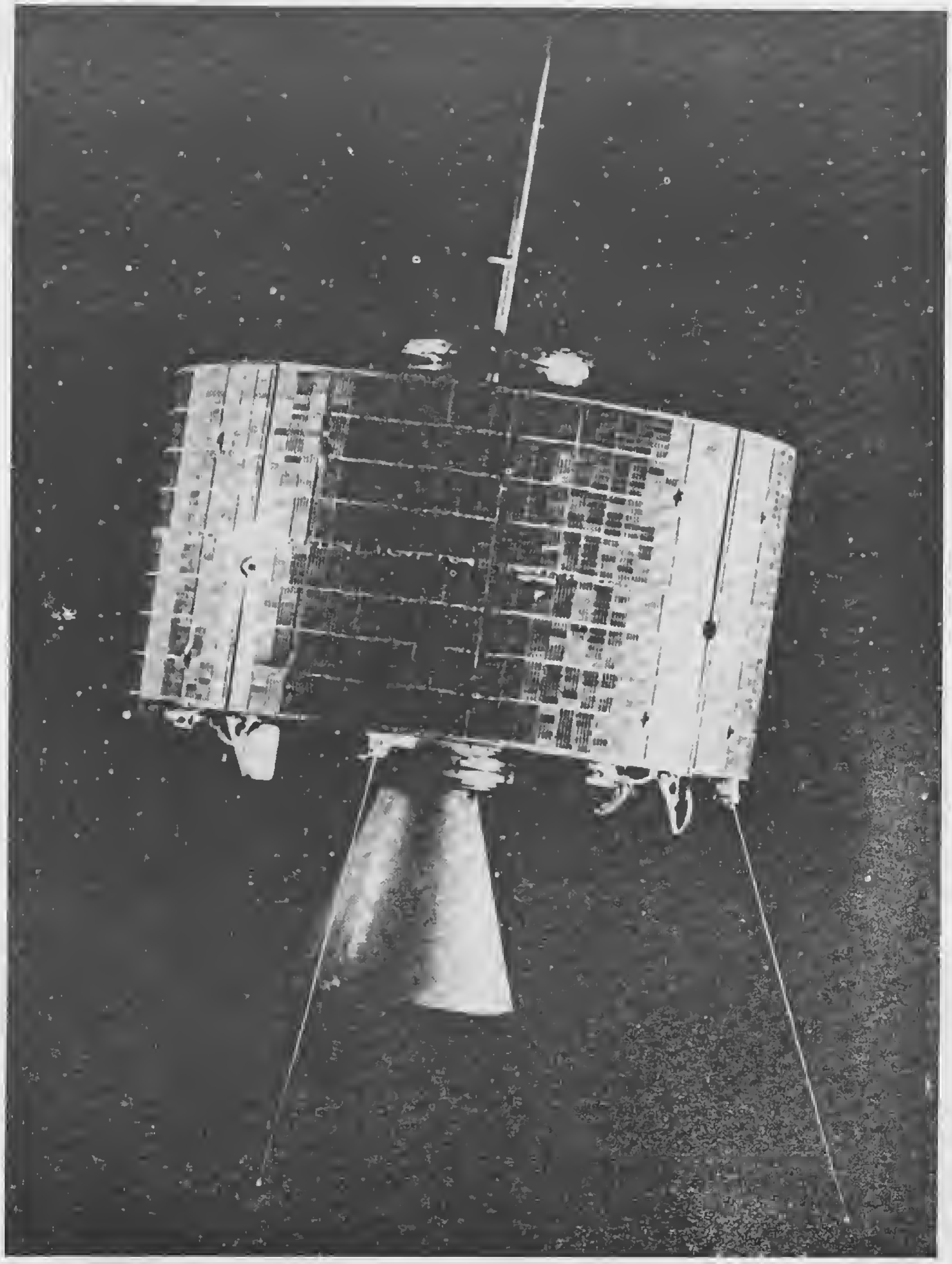

FIGURE 2. Syncom III

As long ago as 1758, Leonhard Euler[2] provided a general solution to the probelm of the rotational motion of a free rigid body. This solution was later expressed in more convenient analytical form, and nearly a century later Poinsot[3] developed an interesting geometrical representation of the solution. Although the general case is somewhat complex, the free motion of a rigid *symmetric* body is not at all difficult, as shown in any basic dynamics text. Among the conclusions drawn from the general solution is the following: *A free rigid body* can spin stably about a principal axis through the mass center corresponding to either *maximum or minimum* moment of inertia, but it is unstable when spinning about the third principal axis, corresponding to an intermediate value of moment of inertia. For an axisymmetric body, the symmetry axis is necessarily either the maximum inertia axis or the minimum inertia axis, so a free, rigid, axisymmetric body is stable when spinning about its axis of symmetry.

Let your attention now shift to the year 1957, and try to put yourself in the shoes of the engineers responsible for Explorer I. Your communications requirements are met if you can make the satellite spin steadily about an axis fixed in the body and fixed in inertial space. You are familiar with the classical results of centuries past, since this is all the textbooks have to offer. You have a very tight schedule. Would you hesitate to design your satellite so as to spin about the principal axis of minimum moment of inertia? Such is the human faith in the printed word that probably you would not hesitate, and since the rocket motor that constitued the last stage of the propulsion system was only six inches in diameter, you would design Explorer I to have the shape shown in Fig. 1.

But ideally an engineer is disciplined to examine critically the assumptions underlying any analysis on which he bases a design. What assumptions are involved in applying the classical stability criterion to the satellite? The answer is available in the language describing this criterion in preceding paragraphs: "*A free rigid body* can spin stably. . . ." A satellite is neither totally free of external forces and torques nor rigid. There are forces and resulting torques due to gravity, solar radiation pressure, electromagnetic interactions, micrometeorite bombardment, and interaction with any trace of the earth's atmosphere at the satellite altitude. But all of these influences are miniscule. Surely when Explorer I is spinning at more than six hundred r.p.m. it will be influenced by these external torques only in the long term. But what about the assumption of rigidity? In Fig. 1 we can see that Explorer I had four antenna wires sticking out from the middle of the satellite. These flexible appendages look a little like lengths of clothesline wire, and they have small tip masses attached to their ends. These masses are such a small percentage of the vehicle mass that they may seem unimportant, and the remainder of the satellite is relatively rigid. How can we evaluate the influence of this local flexibility?

At the Jet Propulsion Laboratory in Pasadena, where men faced the responsibility for launching Explorer I on schedule, this question was not answered until the satellite was launched, and the observed instability made it clear that something had been overlooked. Confronted with this unsettling evidence, the JPL technical staff looked hard for an explanation, and Willard Wells quickly found the answer. He realized that a crucial difference between the classical analyses of rigid body rotations and the motion of a real satellite is in the character of the kinetic energy function. For the *free, rigid* body, the kinetic energy is constant (this follows from the existence of a certain first integral of the equations of motion, and is not a separate assumption). In a real satellite there are always vibrations which cause internal energy dissipation, so the kinetic energy function may be expected to diminish with time. Wells recognized that the wire "whip antennas" would be oscillating wildly when Explorer I was in orbit, and he calculated that the resulting energy dissipation would explain the observed instability. The satellite would be forced to seek that motion corresponding to minimum kinetic energy for the given (constant) angular momentum, and this would require a rotation about the principal axis of maximum moment of inertia. For Explorer I, this meant that the satellite would eventually tumble end over end, and this it proceeded to do with embarrassing speed.

Recognizing that he could not solve the differential equations describing the motion of Explorer I unless he assumed the satellite to be a rigid body, but knowing too that this was the assumption that led to trouble in the first place, Wells adopted an approximate method of analysis which came to be known as the "energy sink approach." Reference 1, Part II contains a description of this method, and an indication of its

use in establishing the *maximum-inertia spin-axis rule*, which says that for spin-stabilization a satellite must spin about the axis through the mass center having the maximum moment of inertia. Wells' application of this approach to Explorer I is contained in an Appendix to the JPL report in Reference 4, and portions of that Appendix are included also in Reference 1.

Of course Explorer I was not man's first artificial earth satellite, and as it turns out the JPL team was not the first to formulate the maximum-inertia spin-axis rule. When Sputnik I was launched in October of 1957, signals were available to observers throughout the world, and from these signals it was possible to deduce rotational motions. In this country, Professor Ronald Bracewell of the Stanford University Radio Propagation Laboratory began tracking Sputnik I almost immediately, and he soon concluded that certain signal oscillations could best be explained by the coning or precessional motion of the spinning vehicle. Although Sputnik I did not provide measurable evidence of the effects of energy dissipation on rotational motion, Professor Bracewell was prompted by his interest in Sputnik I to speculate on the influence of internal energy losses, and he soon arrived at the maximum-inertia spin-axis rule on his own. Professor Bracewell did not have the advantage of information from Explorer I to guide his thinking. His research field did not normally extend to the study of vehicle motions. But he did have the peculiar advantage of familiarity with the rotational motions of galaxies, which give evidence of similar behavior. In personal correspondence with the author in 1965, Professor Bracewell offers the following acknowledgement: "As for the general problem, it is familiar in galactic dynamics. Put collisions into a rotating cloud and it will flatten [because this is the state of minimum kinetic energy for a given angular momentum.] . . . I was aware of these phenomena and believe that the general principle involved was in my mind while working on the satellite problem."

Professor Bracewell presented his conclusions on satellite spin-stabilization to his students in a set of dittoed notes, but this information was not communicated to the men at JPL then working feverishly to prepare Explorer I for launch. (A phone call from Stanford to JPL accomplished nothing because of the cloak of secrecy then surrounding the nation's space program. Security classifications sometimes keep useful information *out* while the unnecessarily classified information is kept within the closed perimeter.) Bracewell was however the first to publish the *maximum-inertia spin-axis rule* in the open literature[5,6]. He also employed "energy-sink" arguments such as those found in Ref. 4.

Unfortunately, not all significant engineering discovery is published, or even documented in internal company reports. Nearly a decade elapsed before it was publicly recognized that the distinction of first formulating the *maximum-inertia spin-axis rule* for satellites belongs to neither Wells nor Bracewell, but may belong to an unheralded innovator named Vernon Landon, who worked in the RCA laboratories for many years.

In February of 1957*, a full year in advance of the launching of Explorer I, Landon had reached the conclusion that made the instability of this satellite an unnecessary surprise. He also employed heuristic arguments, but they differ from Refs. 4-6 in that they rely upon understanding of the immediate influence of dissipative forces. This approach is described in Reference 7, which was not publicly presented until his testimony was invited in 1967. In April of 1957 Landon performed some laboratory tests to confirm his conclusions. But he did not publish his work at that time. In the only contemporary published allusion to this poineering achievement[8], Vernon Landon is not mentioned.

The publication within two months of References 4-6, 8 was enough to alert the space community to the need for caution in spin-stabilization. The response was immediate and dramatic. The maximum-inertia spin-axis rule gained almost universal acceptance despite the absence of general rigorous proof, and

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*Verified by copies of dated worksheets provided to the author in 1965.

throughout the rapidly growing space industry there was a massive effort to capitalize on this discovery by designing satellites of the shape of Syncom (Fig. 2) and developing internal energy dissipation devices designed to accelerate the attenuation of oscillations about the intended spinning motion. A wealth of literature on spin-stabilization marks the period from 1958 to 1964, but virtulaly all of it operates within the framework established by the maximum-inertia spin-axis rule, rather than seeking its modification or formal confirmation (See Ref. 9 for a summary of this work.). As the papers were published and the spin-stabilized satellites were successfully flown, this heuristically generated rule-of-thumb assumed increasingly the image of a sacred and inviolable law.

Questions

1. *The* maximum-inertia spin-axis rule *for satellite spin-stabilization was predicted without benefit of experimental evidence by Landon, it was noted again after Sputnik I by Bracewell, who was aware of relevant observations of galaxies, and finally it was discovered by Wells after the anomalous performance of Explorer I. Each of these men had different amounts of experimental evidence to guide his thinking. Consider your experience with other new concepts in science and technology. Do new ideas often spring fully formed from the minds of men, or are we usually just groping to explain some puzzling observations?*

2. *The* maximum-inertia spin-axis rule *applies not only to spacecraft, but to any material system free of external torques. This is a simple idea, only a step beyond the 1758 solutions of Euler, and an "obvious" extension of the 1834 work of Poinsot. Yet until 1957 the idea was apparently never formulated, and then within a year it was discovered three times. What does this suggest concerning the phrase "an idea whose time has come" and the old adage "necessity is the mother of invention?" Can you think of other examples?*

III. The evolution of the dual-spin attitude stabilization concept

The maximum-inertia spin-axis rule seemed in 1958 to be a satisfactory resolution of the spin-stabilization problem. Once the rule was recognized, there was at first little difficulty in designing satellites that were stable by virtue of being roughly coin-shaped rather than pencil-shaped. But as satellites grew in size this became an increasingly oppressive constraint, largely because of the necessity of fitting the satellite within a shroud mounted on a rocket of limited diameter. The time was ripe for the discovery of a way to circumvent this rule.

Vernon Landon pursued this question at RCA as circumstances permitted. By early 1962 his appreciation of the qualitative behavior of damping forces led him to realize that the maximum inertia constraint for attitude stability does not apply to spinning satellites with angular momentum sufficiently augmented by a rigid rotor. Landon's original explanation of the stabilizing or destabilizing tendencies of a damper on a spinning satellite was simple and direct. (Reference 7, written five years later, retains the substance of the original presentation.) Appreciation of the sense of his argument is basic to a genuine understanding of dual-spin attitude stabilization. Yet, when Landon sought to publish his results in a prominent astronautical journal, his pioneering paper was rejected. Because the presentation was lacking in the mathematical rigor that marks most journal publications, and the significance of the results was not clearly communicated, this rejection was not incompatible with research journal standards, but with hindsight it appears an unfortuante rejection indeed.

Vernon Landon was not entirely thwarted in his attempts to gain recognition; with the help of Brian Stewart he later provided a new energy sink argument which was published[10] in late 1964. But by that time the dual-spin attitude stabilization concept had been discovered and extensively developed by Anthony Iorillo of Hughes Aircraft Company, and Ball Brothers Research Corporation had already gained flight experience with the Orbiting Solar Observatory (OSO) dual-spin satellites (see Fig. 3).

The OSO design concept was established in about 1959, when the maximum-inertia spin-axis rule was still a new idea. The major portion of the satellite was to spin for attitude stabilization, but a significant part of the vehicle was despun or counter-rotated in order to maintain an attitude facing the sun. (In Fig. 3 the lower half of the vehicle spins and the upper half faces the sun.) The solar telescope and solar cells for power generation were on the despun platform, as was the passive damper which dissipated energy to make the oscillations about the stable motion decay. Since during part of the mission the entire vehicle was to rotate in one piece, the satellite was carefully designed so that the spin axis was the axis of maximum moment of inertia. The Ball Brothers staff did of course confirm the fact that in the dual-spin mode of operation their satellite would also be stable, but somehow they did not perform a stability analysis in sufficient generality to recognize that the OSO satellites in the dual-spin mode of operation would have been stable even if they had violated the maximum-inertia spin-axis rule. This oversight persisted until early 1966, when Thomas Spencer happened upon this conclusion while exercising a new OSO digital computer simulation he had developed for Ball Brothers. By that time the Landon/Stewart paper had been published, and Tony Iorillo had persuaded Hughes Aircraft Company to base their proposal for a multi-million dollar communications satellite on his new idea for dual-spin attitude stabilization.

Iorillo's discovery of the dual-spin concept had a different stimulus than Landon's or Spencer's. His original objective was to determine what new stability criterion would result if a despun earth-pointing antenna were to be attached to a spinning satellite such as Syncom. There was no immediate objective of circumventing the maximum-inertia spin-axis rule, and indeed in the original Hughes Interdepartmental Correspondence describing his analysis Iorillo ends his concluding remarks with the sentence: "Thus, when a despun section is added to Syncom, the configuration must be designed such that $C/A > 1$," where C is the moment of inertia about the spin axis of the spinning part of the satellite and A is the transverse inertia of the entire vehicle. This conclusion seems still to imply the *maximum-inertia spin-axis rule* only because in this final sentence Iorillo assumed that the damper was on the rotating portion of the dual-spin satellite. Elsewhere in this memo it is apparent that the analysis is not restricted to this damper location, and the vehicle is stable without inertia restriction if the damper is on a despun platform.

Tony Iorillo began at Hughes Aircraft Company a remarkable program to develop his idea technically and promote it with his management. He took the important step of extending his analysis to accommodate in an approximate way the loss of energy in both rotor and platform simultaneously, and presented his results in 1965.[11] Without this crucial extension, the dual-spin attitude stabilization concept was an abstraction, with little assurance of practical realizability. In the following year Hughes Aircraft Company proposed to the Air Force a communications satellite based on Iorillo's concept. Because the proposed satellite violated the maximum-inertia spin-axis rule, it was met with some skepticism by the Air Force evaluation team at the Aerospace Corporation. But the concept was examined from all sides[12,13,14], and the Air Force was convinced. The contract was awarded in late 1966, and in early 1969 the first dual-spin satellite violating the maximum-inertia spin-axis rule was successfully placed in orbit (See Fig. 4).

The story of the dual-spin attitude stabilization concept is far from complete, but the first chapters have been written. There are in 1969 many dual-spin spacecraft in planning stages throughout the space industry, even while we are still learning from the behavior of the first such satellite new things about the implementation of this concept. A growing body of literature provides a wealth of analysis to explore (See References), and the volume of dual-spin spacecraft research is still growing. An Air Force Symposium on dual-spin spacecraft[15] was instrumental in assuring the rapid dissemination of information on the dual-spin concept, and, after initial rejection and years of delay, this remarkable technological breakthrough became an overnight sensation!

Questions:

1. *Comment on the parallel between the discovery of the maximum-inertia spin-axis rule for quasirigid spinning vehicles and the dual-spin attitude stability criterion for dual-spin vehicles. Discuss the differing roles played by Explorer I and OSO I in the discovery of these two concepts. Were either of these ideas conceived as the result of rigorous mathematical analysis, or were these discoveries guided*

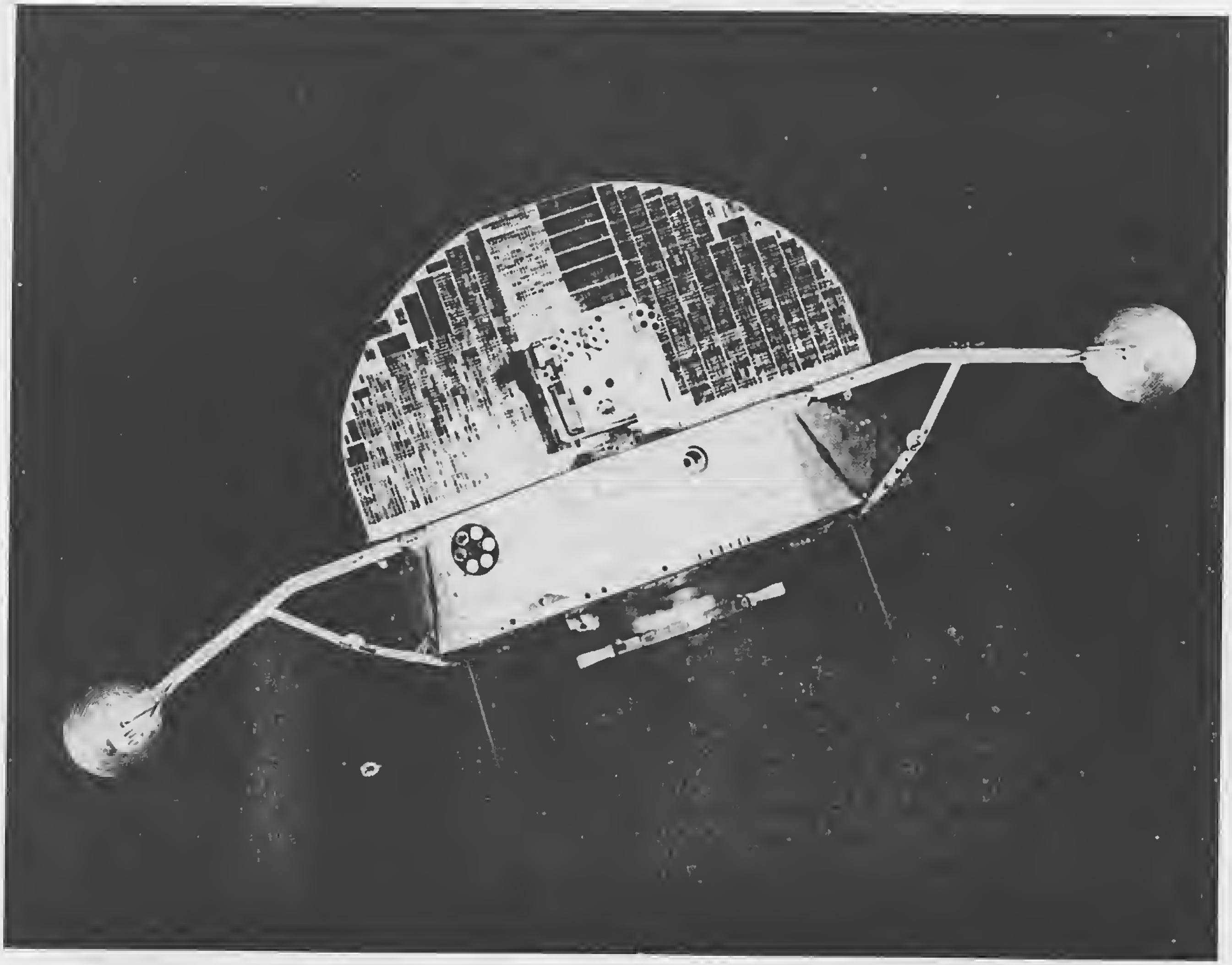

FIGURE 3. Orbiting Solar Observatory OSOI

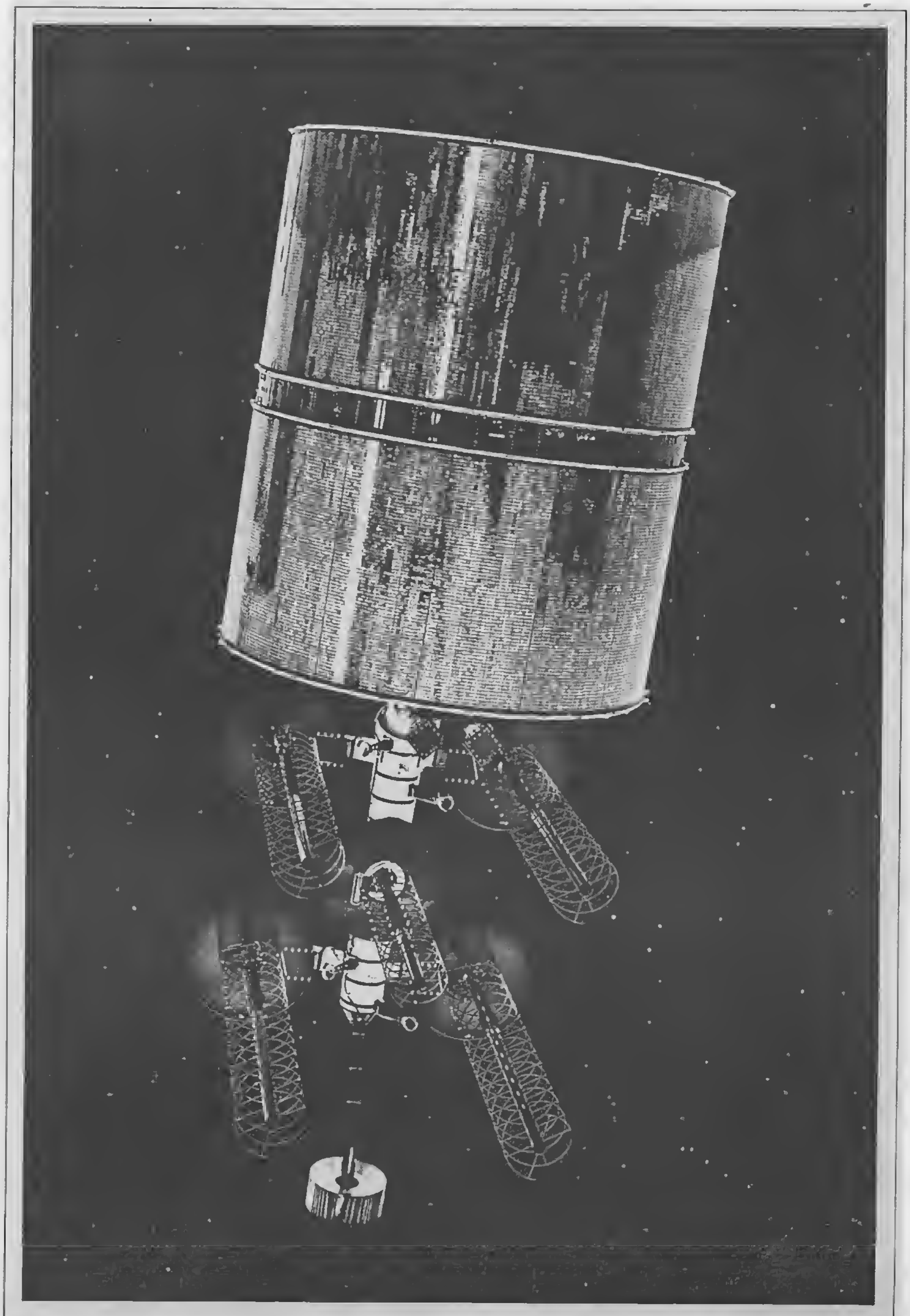

FIGURE 4. Experimental Tactical Communications Satellite

by heuristic thinking? Did heuristic argument serve to impede *the acceptance of these ideas in some minds while it served to promote understanding in other minds? What is the role of rigorous mathematical analysis in the development of these ideas? In these cases was the technological breakthrough the result of the activities of "project engineers," "research engineers," or both?*

2. *What does it take to transform a good technical idea into a revolutionary influence in the aerospace industry?*

IV. Guide to further reading

The list of references provides rather complete documentation of the open literature on the dual-spin attitude stabilization concept published prior to 1970, together with a few background sources. No attempt has been made to include the extensive literature found in company reports, which are often not available for unrestricted dissemination.

Although (with the exception of Ref. 1), the papers listed are written for research documentation rather than general education, an undergraduate engineering student can gain a satisfactory understanding of fundamental phenomena by reading (together with Ref. 1) the material in Refs. 5 and 7.

The beginnings of analytical complexity are found in Refs. 11-14, but these papers must be included in any systematic exploration of the basic concept of dual-spin attitude stabilization.

Reference 15 is a compilation of papers presented at a symposium which marked the beginnings of general acceptance of the dual-spin concept. References 7, 13 and 14 are included, as are two papers by Spencer (who was mentioned as the third independent discoverer of dual-spin attitude stabilization) and a paper by Iorillo (who must be recognized as the man who carried the concept to the implementation stage).

References 16 and 17 treat fundamental questions of stability analysis raised by dual-spin satellites, and are of theoretical interest.

The remaining publications are included on the reference list in order to provide the researcher with a starting point for further investigation. This inquiry may be assisted by the knowledge that the word "gyrostat" as it appears in many of the titles is classically defined to mean a rigid body in which is rigidly embedded the axis of a rigid axisymmetric rotor. Thus a gyrostat is a highly idealized version of a dual-spin satellite, just as a rigid body is an idealized version of a "spinner" or spin-stabilized satellite.

References

1. *Bollay, W., "Spin Stability of the Explorer Satellite," Engineering Case Library Case Study No. ECL 1006, 1967.*

2. *Euler, L., "Memoires de Berlin," 1758.*

3. *Poinsot, H., "Theorie Nouvelle de la-Rotation des Corps," Paris, 1834 (also in "Journal de Liouville," tomXVI, 1851).*

4. *Pilkington, W. C., "Vehicle Motions as Inferred from Radio Signal Strength Records," External Publication No. 551, Jet Propulsion Laboratory, Pasadena, September 5, 1958.*

5. *Bracewell, R. N. and Garriot, O. K., "Rotation of Artificial Earth Satellites,"* Nature *182, 760-762, September 20, 1958.*

6. *Bracewell, R. N., "Satellite Rotation,"* Advances in the Astronautical Sciences, *Vol. 4, 1958, pp. 317-328.*

7. *Landon, V. D., "Early Evidence of Stabilization of a Vehicle Spinning About Its Axis of Least Inertia,"* Proceedings of the Symposium on Attitude Stabilization and Control of Dual-Spin Spacecraft, *1-2 August, 1967, Air Force Report No. SAMSO-TR-68-191 and Aerospace Corporation Report No. TR-0158(3307-01)-16 November, 1967.*

8. *Perkel, H., "Space Vehicle Attitude Problems,"* Advances in the Astronautical Sciences, *Vol. 4, 1958, pp. 173-192.*

9. *Likins, P. W., "Effects of Energy Dissipation on the Free Body Motions of Spacecraft,"* Jet Propulsion Laboratory TR 32-860, *July 1, 1966.*

10. *Landon, V. D., and Stewart, B., "Nutational Stability of an Axisymmetric Body Containing a Rotor,"* J. Spacecraft and Rockets *1, 682-684, 1964.*

11. *Iorillo, A. J., "Nutation Damping Dynamics of Axisymmetric Rotor Stabilized Satellites," ASME Winter Meeting, Chicago, Illinois, November, 1965. See also "Analyses related to the Hughes Gyrostat System," a collection of four papers by Iorillo published by Hughes Aircraft Company in December, 1967.*

12. *Likins, P. W., "Attitude Stability Criteria for Dual-Spin Spacecraft,"* J. Spacecraft and Rockets *4, 1638-1643 (1967).*

13. *Velman, J. R., "Simulation Results for a Dual-Spin Spacecraft,"* Proceedings of the Symposium on Attitude Stabilization and Control of Dual-Spin Spacecraft, *1-2 August, 1967, Air Force Report No. SAMSO-TR-68-191 and Aerospace Corporation Report No. TR-0158(3307-01)-16, November, 1967.*

14. *Mingori, D. L., "Effects of Energy Dissipation on the Attitude Stability of Dual-Spin Satellites,"* AIAA J. *7, 20-27 (1969).*

15. Proceedings of the Symposium on Attitude Stabilization and Control of Dual-Spin Spacecraft, *1-2 August, 1967, Air Force Report No. SAMSO-TR-68-191 and Aerospace Corporation Report No. TR-0158(3307-01)-16, November, 1967.*

16. *Likins, P. W. and Mingori, D. L., "Liapunov Stability Analysis of Freely Spinning Systems,"* Proc. of 18th International Astronautical Congress, *(Belgrade, 1967), pp. 89-102, Pergamon Press, New York, 1968.*

17. *Pringle, Jr., R. "The Stability of the Force-Free Motions of a Dual-Spin Spacecraft,"* AIAA J. *7, 1054-1063 (1969).*

18. *Kane, T. R and Mingori, D. L., "Effect of a Rotor on the Attitude Stability of a Satellite in Circular Orbit,"* AIAA J. *3, 936-940 (1965).*

19. *Gutman, A. S., "Gravity-Gradient Stabilization for a Spinning Satellite with Despun Line of Sight,"* J. Spacecraft and Rockets *2, 584-590 (1965).*

20. *Anchev, A. A., "Flywheel Stabilization of Relative Equilibrium of a Satellite,"* Kosmicheskie Issledovaniya *4, 192-202 (1966).*

21. *Roberson, R. E. and Hooker, W. W., "Gravitational Equilibria of a Rigid Body Containing Symmetric Rotors,"* Proc. of the 17th International Astronautical Congress *(Madrid, 1966).*

22. *Spencer, T. M., "Nutation Damping for Dual-Spin Spacecraft," presented at the American Astronautical Society Symposium on Rocky Mountain Resources for Aerospace Science and Technology, Denver, Colorado, July 13-14, 1967.*

23. *Rumiantsev, V. V., "On the Stability of Stationary Motions of a Satellite With a Rotor and Cavity Containing Fluids,"* Kosmicheskie Issledovaniya *5, 163-169 (1967).*

24. *Hughes, W. G., "Nutational Stability of Multi-body Spin-Stabilized Satellites,"* Proc. of the 18th International Astronautical Congress *(Belgrade, 1967), Pergamon Press, New York, 1968.*

25. *Rumiantsev, V. V., "On Stability of Stationary Motions of the Gyrostat Satellite,"* Proc. of the 18th International Astronautical Congress *(Belgrade, 1967), Pergamon Press, New York, 1968.*

26. *Roberson, R. E., "Equilibria of Orbiting Gyrostats,"* J. Astronaut. Sci. 15, *(1968).*

27. *Cloutier, G. J., "Stable Rotation States of Dual-Spin Spacecraft,"* J. Spacecraft and Rockets *5, 490-492 (1968).*

28. *Porcelli, G., "Optimal Altitude Control of a Dual-Spin Satellite,"* J. Spacecraft and Rockets *5, 881-888 (1968).*

29. *Austin, F., "Stability Criteria for a Rotating Space Station with a Nonrotating Hub,"* AIAAJ. *6, 2211-2213 (1968).*

30. *Fang, B. T. "Energy Considerations for Attitude Stability of Dual-Spin Spacecraft,"* J. Spacecraft and Rockets *5, 1241-1243 (1968), See also Comments by D. L. Mingori and W. J. Russell in* J.S.R. *6, 350-352 (1969).*

31. *Puri, N. N., and Guido, J. F., "Nutational Stability Criteria for a Dual-Spin Spacecraft—The Damper Reaction Torque and Quadratic Function Method," presented at the 19th International Astronautical Congress, New York, 1968.*

32. *White, E. W. and Likins, P. W., "The Influence of Gravity Torque on Dual-Spin Satellite Attitude Stability,"* J. Astronaut. Sci. *16, 32-37. (1969).*

33. *Longman, R. W. and Roberson, R. E., "General Solution for the Equilibria of Orbiting Gyrostats Subject to Gravitational Torques,"* J. Astronaut. Sci. *16, 49-59 (1969).*

34. *Cloutier, G. T., "Nutation Damper Design Principles for Dual-Spin Spacecraft,"* J. Astronaut. Sci. *16, 59-68 (1969).*

35. *Cloutier, G. J., "Nutation Damper Instability on Spin-Stabilized Spacecraft,"* AIAA J. *7, 2110-2115 (1969).*

36. *Bainum, P. M., Fuechsel, P. G., and Mackison, D. L., "On the Motion and Stability of a Dual-Spin Satellite with Nutation Damping," presented at AIAA Guidance, Control, and Flight Mechanics Conference, Princeton, N. J., 1969.*